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COMPARISON OF OPTICALLY-ADDRESSED SPATIAL LIGHT MODULATORS

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The performance characteristics of three unique optically-addressed spatial light modulator (SLM) structures have been experimentally investigated. The measured parameters include maximum resolution, visibility, imaging response time, and write light sensitivity. The modulators investigated include two relatively new technologies: the ferroelectric liquid crystal (FLC) SLM from the University of Colorado-Boulder and the amorphous silicon photoconductive twisted nematic liquid crystal SLM from GEC-Marconi Research, and a well established industry benchmark, the Hughes Liquid Crystal Light Valve (LCLV). A comparison of these devices in terms of the above performance parameters is discussed in this report.

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I. INTRODUCTION

A major technological hurdle for optical computing and optical pattern recognition is the current state of performance of Spatial Light Modulators (SLMs). An SLM is a device that yields an image in coherent light from either an incoherent light or electrical signal input. The slow response, low resolution, and high cost of spatial light modulators present significant limitations in optical computing and pattern recognition. Several optically-addressed modulators have been constructed in recent years which could potentially overcome some of the limitations of the most well-known modulator - the Liquid Crystal Light Valve [1]. The more recent devices include ferroelectric liquid crystal (FLC) SLMs [2-4] and a GEC-Marconi Research liquid crystal SLM [5].

This communication is a compilation of operating parameters and performance of the above modulators investigated at the U. S. Army Missile Command. The parameters investigated are conducive to understanding the utility of these modulators as input image transducers in optical correlator architectures. The resolution, visibility, and response time of these modulators were measured and are presented here for comparison.

II. RESOLUTION MEASUREMENTS

The experimental system shown in figure 1 was used to measure the resolution of the candidate SLMs. A HeNe laser (λ=632.8 nm) was spatially filtered and collimated using standard laboratory techniques. A polarizing beamsplitter was used to direct the HeNe beam to the read side of the SLM. Lenses L2 and L3 were used to image the modulated read beam onto a CCD camera. The position and focal length of lenses L2 and L3 were chosen to provide a 4:1 magnification of the modulated read beam. The input polarizer and polarizing beamsplitter were also oriented for optimum image visibility at the CCD plane. An Argon ion laser was employed as the write light source. The argon laser was also spatially filtered and collimated using standard laboratory techniques. The collimated argon beam (λ=514.5 nm) was incident on a chrome-on-glass transparency of a USAF Resolution Chart. The illuminated chart was then imaged onto the write side of the SLM using lens L1, a 50 mm f.l. compound lens assembly. The focal length and position of the lens were chosen for unity magnification of the chart onto the SLM write surface. Initially, no SLM was present in the test system in order to measure the maximum resolution of the imaging optics. A photograph of the resultant image is shown in figure 2. The smallest resolvable segment of the USAF resolution chart was found in group #6, element #5 which corresponds to a maximum resolution of 102 lp/mm.

A Hughes liquid crystal light valve was initially tested with the above system. The Hughes LCLV employs CdS as the photoconductor and a twisted nematic liquid crystal structure as the active modulating medium [1]. Maximum resolution was achieved when this device was driven by a 1.92 KHz, 9.96 V amplitude sinusoidal waveform while the incident read and write beam intensities corresponded to 140 $\mu W/cm^2$ each. A photograph of the modulated read beam image is shown in figure 3(a). The maximum resolution was found in group #5, element #1 which corresponds to 40 lp/mm. This particular LCLV was fabricated in the late 70s. This modulator was replaced in the optical testbed with a more recently fabricated LCLV, also manufactured by

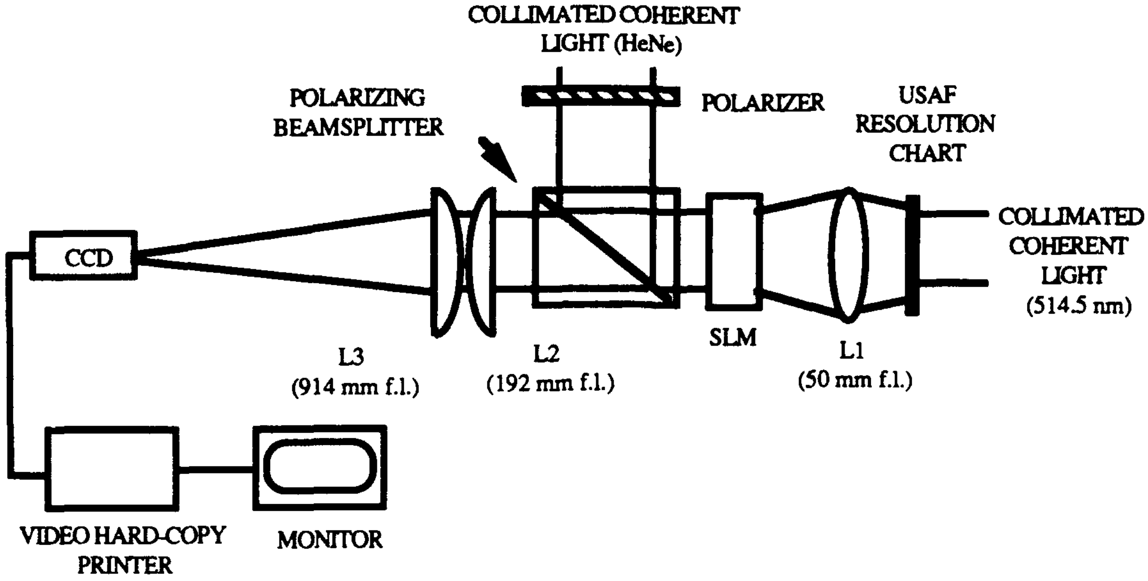


Figure 1. Schematic Representation of the Experimental System Used to Measure the Maximum Resolution of the Candidate Spatial Light Modulators

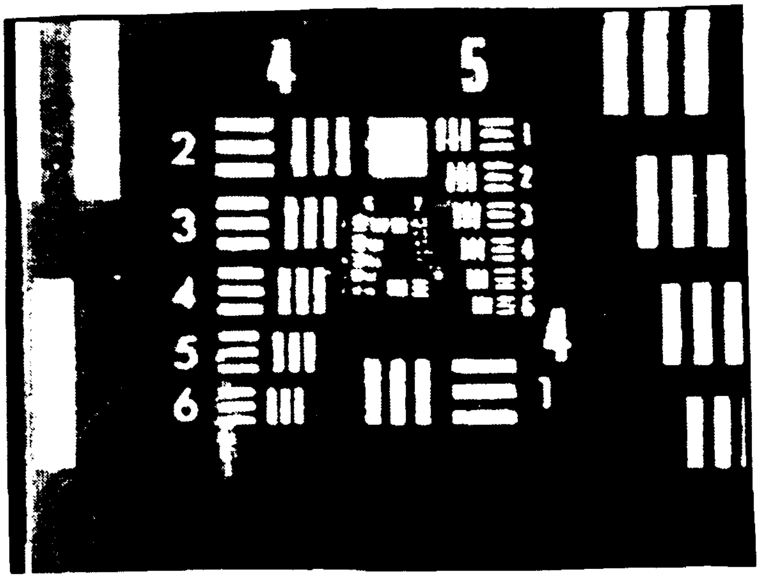
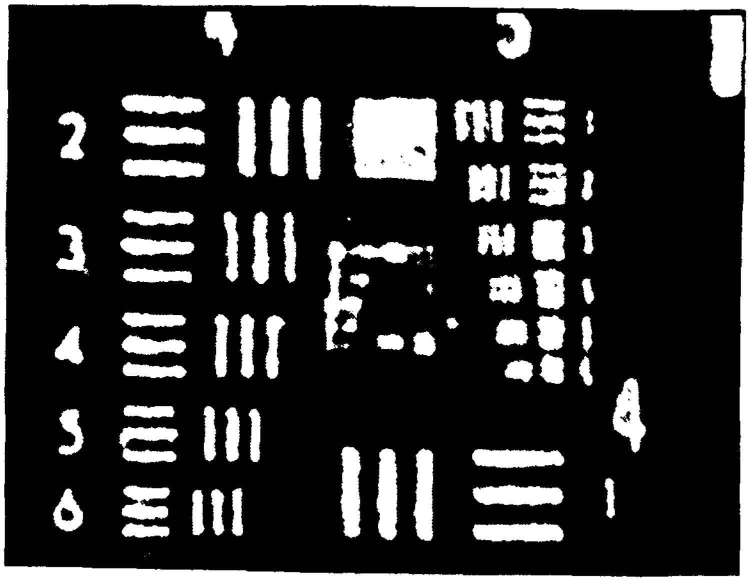
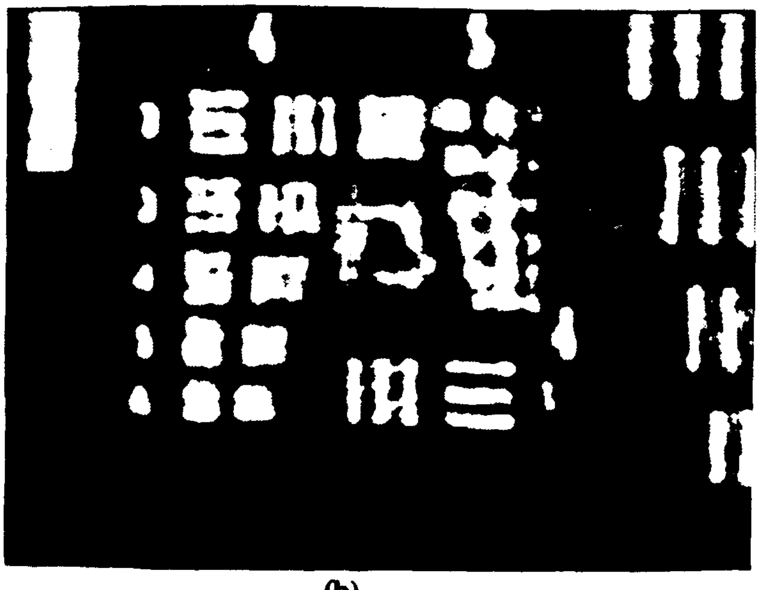


Figure 2. Resultant Image of the USAF Resolution Chart Imaged by the System Shown in Figure 1 Without an SLM Present. The Resolution Limit of the Imaging Optics is 102 lp/mm

Hughes. This more recent LCLV also employed CdS and a twisted nematic liquid crystal structure. The intensities of the write and read beams were measured to be 100 and 80 $\mu W/cm^2$, respectively. The driving waveform and read beam polarization were adjusted until maximum resolution was observed at the CCD plane. Maximum resolution was determined to be 22.6 lp/mm (group #4, element #4) as shown by the photograph in figure 3(b). The driving waveform corresponding to this maximum resolution condition was a 4 KHz, 7.97 V sinusoid.



(a)



(b)

Figure 3. Resolution of the Hughes LCLVs in the Experimental System of Figure 1

The Hughes LCLVs were then replaced with an optically-addressed SLM available from GEC-Marconi Research. This SLM utilizes hydrogenated amorphous silicon as the photoconductor and a twisted nematic liquid crystal structure as the modulating medium [5]. Again, the driving waveform and read beam polarization were adjusted until maximum resolution was observed at the CCD plane. Initially, the write light incident on the SLM corresponded to 600 $\mu W/cm^2$. Maximum resolution was determined to be 71.8 lp/mm while the driving waveform of the SLM was a 5 KHz, 3.5 V sine wave. Alternatively, maximum resolution was determined to be 64 lp/mm (group #6, element #1) for lower write light intensities (100 $\mu W/cm^2$). This resolution measurement for low write light intensities occurred when the GEC-Marconi SLM was driven by a 1.5 KHz, 2 V square wave with a +1 V DC offset. A photograph of the corresponding image is shown in figure 4.

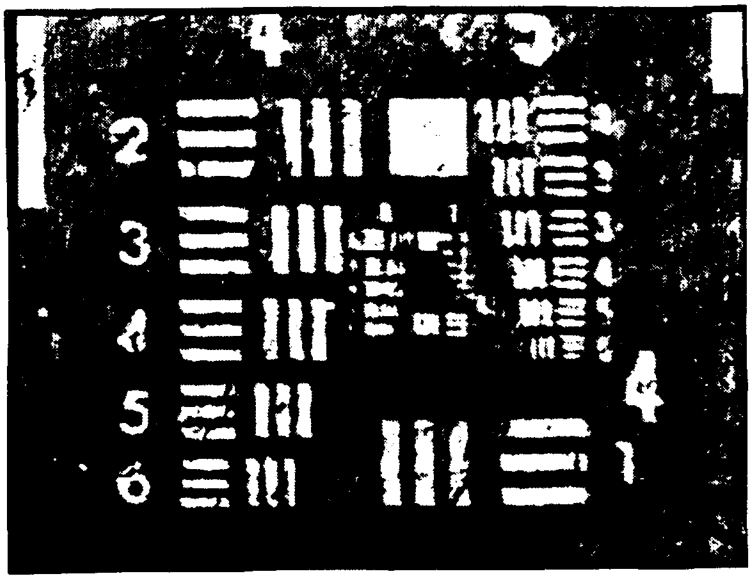


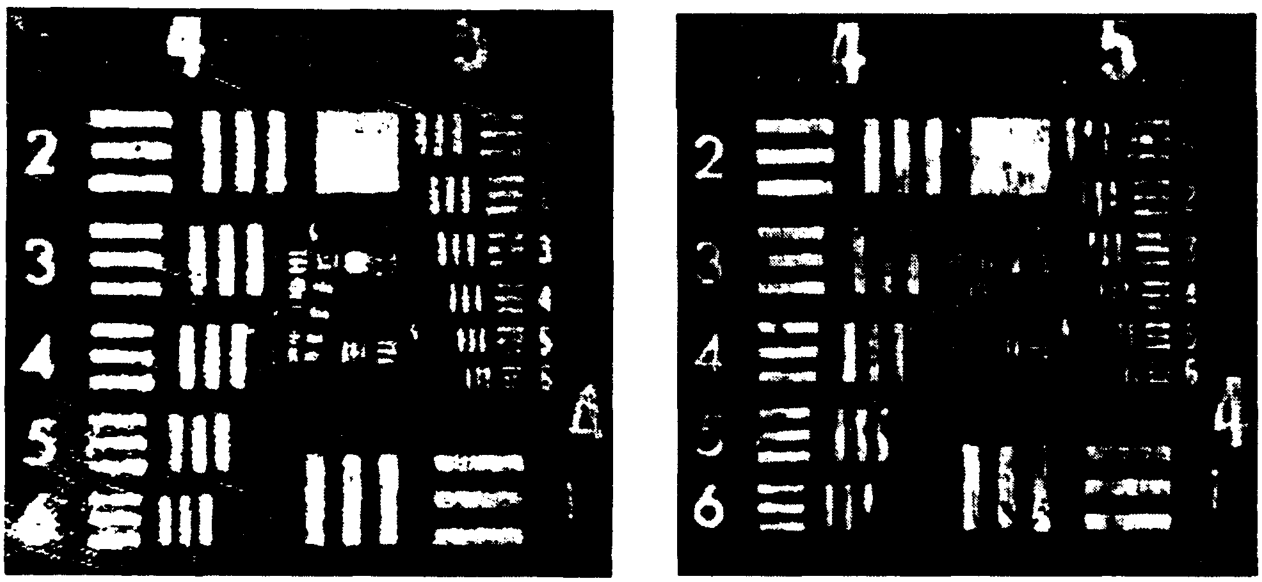
Figure 4. Resolution of the GEC-Marconi Research SLM in the Experimental System of Figure 1

The GEC-Marconi SLM was then replaced by an optically-addressed ferroelectric liquid crystal (FLC) SLM fabricated by the University of Colorado-Boulder and Displaytech, Inc. The basic structure of this modulator has been discussed elsewhere and will not be presented here [2]. Optimum resolution was observed when the incident write beam intensity corresponded to 300-500 $\mu W/cm^2$. Maximum resolution was determined to be 71.8 lp/mm when the incident write light intensity corresponded to 300 $\mu W/cm^2$. For optical correlation applications at the U. S. Army Missile Command, lower write light intensities are usually needed. The write beam was attenuated with a variable beamsplitter until 100 $\mu W/cm^2$ was incident on the FLC SLM write surface. The driving waveform and read beam polarization were adjusted until maximum resolution and image visibility occurred. The optimum resolution and visibility were both very low. The sensitivity of the device to input scenes corresponding to the above stated intensity was immeasurable. The write beam intensity was then increased to 200 $\mu W/cm^2$ incident on the FLC SLM. This intensity was a compromise between the write light intensity required to achieve

maximum resolution and the intensity commonly needed in MICOM optical correlator architectures. Maximum resolution was determined to be 64 lp/mm at 200 $\mu W/cm^2$ incident write light while the driving waveform was a 1.25 KHz, 15 V square wave with a +5 V DC offset. A photograph of the resultant image is shown in figure 5(a).

A second FLC SLM was tested in the system depicted by figure 1. This FLC SLM was also fabricated by the University of Colorado-Boulder and Displaytech, Inc. At 500 $\mu W/cm^2$ incident write beam intensity, maximum resolution was determined to be 102 lp/mm while the driving waveform was a 1 KHz, 9 V square wave with a +3 V DC offset. This resolution measurement corresponds to the maximum resolution of the imaging optics of the testbed. Therefore, the maximum resolution may well be greater than 100 lp/mm for a 500 $\mu W/cm^2$ incident write light intensity. Again, the write beam was attenuated with a variable beamsplitter until the incident light on the write surface of the SLM corresponded to 200 $\mu W/cm^2$. The maximum resolution was determined to be 71.8 lp/mm (group #6, element #2) for this condition. The driving waveform of the device was a 1 KHz, 10 V square wave with a +5 V DC offset. A photograph of the resultant image is shown in figure 5(b).

The above resolution measurements are summarized in Table 1 along with the resolution corresponding to 50% visibility discussed in the following section.



(a) (b)

Figure 5. Resolution of the Ferroelectric Liquid Crystal SLMs in the Experimental System of Figure 1

Table 1. Summary Table of SLM Resolution and Visibility Measurements

SLM	MAX. RESOLUTION	RESOLUTION@0.50	WRITE INTENSITY
HUGHES LCLV	40 lp/mm	20 lp/mm	140 µW/sq.cm.
PCU SLM (Hughes LCLV)	22 lp/mm	18 lp/mm	100 µW/sq.cm.
GEC-Marconi Research SLM	64 lp/mm	32 lp/mm	100 µW/sq.cm.
FLC #1 SLM	64 lp/mm	40 lp/mm	200 µW/sq.cm.
FLC #2 SLM	71.8 lp/mm >102 lp/mm	20 lp/mm -------	200 µW/sq.cm. 500 µW/sq.cm.

III. VISIBILITY MEASUREMENTS

The experimental system shown in figure 6 was used to measure the visibility of the candidate SLMs. The system shown in figure 6 differs from the one shown in figure 1 by the addition of a Colorado Video model 321 video analyzer and a strip–chart recorder. The output

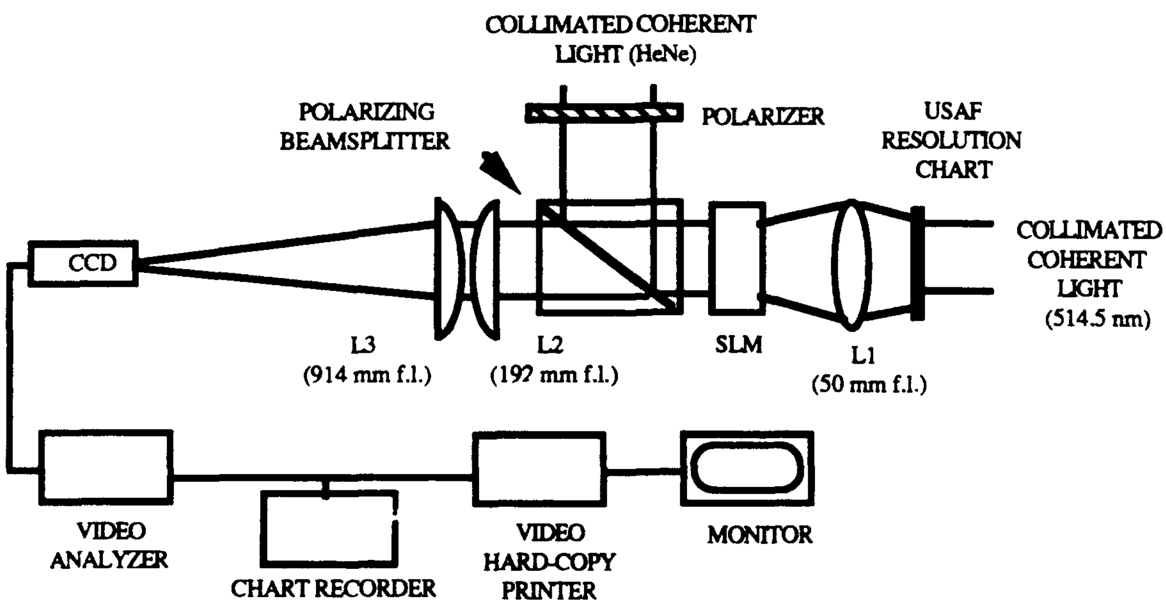


Figure 6. Schematic Representation of the Experimental System Used to Measure the Visibility of the Candidate Spatial Light Modulators

video of the CCD camera was channeled to the video analyzer. The analyzer was then used to perform a horizontal or vertical scan across each group and element of the USAF resolution image. The relative intensity of the scans was recorded via a OmniScribe D5000 series chart recorder. Following Michelson [6], visibility is defined as:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where I_{max} and I_{min} are the maximum and minimum intensities of the resulting image. The visibility of each group and element number was determined using the above technique. The group and element number of the USAF resolution image corresponding to a visibility of 0.50 for each SLM was particularly noted.

The resolution corresponding to 50% visibility for each of the above modulators was determined using the same conditions of operation (write light intensity and driving waveform) for each of the modulators described above. A summary of these measurements is shown in Table 1.

IV. RESPONSE TIME MEASUREMENTS

The response times of the candidate modulators were measured using the experimental system shown in figure 7. The inclusion of an electronic shutter in the write beam and a modification of the read beam output optics are the key differences between this testbed and the one described in figure 1. Lenses L2 and L3 of figure 1 were replaced with a single 254 mm focal length bi-convex lens. This lens was chosen to capture the entire modulated read beam onto a Newport Research Corporation model 815-SL power meter/ photodetector assembly. The analog output of the power meter was then sampled using an A/D data acquisition board located within an IBM AT chassis. Alternatively, the output of the power meter could be viewed with an oscilloscope.

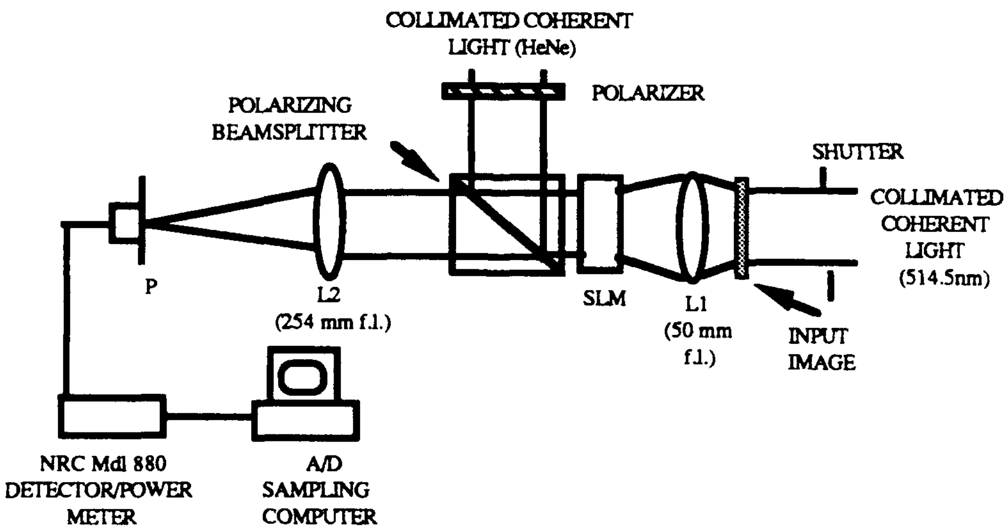
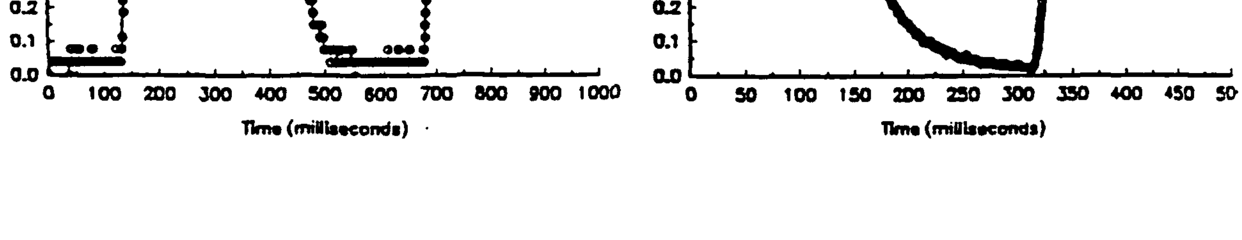


Figure 7. Schematic Representation of the Experimental System Used to Measure the Response of the Candidate Spatial Light Modulators

Prior to collection of data using this system, the response time limitation of the shutter, detector, and A/D acquisition was determined. The detector was positioned in front of the shutter of the write beam, which was cycled open and closed every 40 milliseconds. The A/D board sampled the output of the detector every 0.2 milliseconds during this cycling. The rise and fall times were determined to be approximately one millisecond each for the shutter/detector combination. Therefore, the detector, shutter, and A/D acquisition process should not limit the response measurement of the candidate modulators until about 500 Hz.

The Hughes LCLVs were first tested using the system described above. The shutter, and therefore the write beam incident on the modulator, was cycled "on" and "off" for each modulator. The analog output of the photodetector was sampled and the resultant plots of response time for the two Hughes LCLVs are shown in figure 8. The write and read beams incident on the late 1970s LCLV corresponded to 100 $\mu W/cm^2$ and 80 $\mu W/cm^2$ intensity, respectively. Response of SLMs is typically quoted as a function of two values - rise and fall times. Furthermore, the rise time is typically quoted from the 10% to 90% of full modulation whereas fall time is quoted as 90% to 10% of full modulation. The 10-90% rise time was measured as 22 milliseconds whereas the 90-10% fall time was measured as 52 milliseconds for a total cycle time of 74 milliseconds. Alternatively, the 0-100% rise time was measured as 35 milliseconds, the 100-0% fall time was 77 milliseconds, and the total cycle time was 112 milliseconds. The response of the more recently fabricated Hughes LCLV was also measured. The response was measured with incident write and read beam intensities of 200 and 80 $\mu W/cm^2$, respectively. The 10-90% rise time was determined to be 27 milliseconds whereas the 90-10% fall time was 77 milliseconds. Alternatively, the 0-100% rise time was 54 milliseconds and the 100-0% fall time was 140 milliseconds for this device.



(a) (b)

Figure 8. Response Data of (a) the Late 70s Hughes LCLV and (b) the More Recently Fabricated Hughes LCLV

The Hughes LCLVs were replaced with the GEC-Marconi Research SLM in the experimental system depicted in figure 7. The resultant response curve is shown in figure 9. The 10-90% rise time was measured to be 6 milliseconds while the 90-10% fall time was 19 milliseconds. The 0-100% rise time was determined to be 11 milliseconds whereas the 100-0% fall time was 40 milliseconds. The write and read beam intensities corresponding to these measurements were 100 and 10 $\mu W/cm^2$, respectively.

The GEC-Marconi SLM was then replaced with the earlier version of the ferroelectric liquid crystal SLM fabricated by the University of Colorado-Boulder and Displaytech, Inc. The response of this modulator was measured using the techniques described above. The resultant response curve is shown in figure 10(a). The 10-90% rise time was measured to be 5 milliseconds whereas the 90-10% fall time was determined to be 4 milliseconds. The 0-100% rise time was measured to be 10 milliseconds whereas the 100-0% fall time was determined to be 8 milliseconds. These response measurements occurred at 600 $\mu W/cm^2$ write light intensity and 25 $\mu W/cm^2$ read light intensity. A detailed analysis of the response of this particular SLM has been previously reported [7].

The SLM was then replaced with a more recently fabricated FLC SLM also from the University of Colorado-Boulder and Displaytech, Inc. The electronic shutter was cycled open and closed at a 5 Hz frequency. A high frequency modulation observed on the response curve was due to the device being driven by the 1.0 KHz square wave voltage. The reason that the output of the device oscillates at this frequency is because the device at least partially erases during the forward-bias portion of the square wave cycle. Ideally, the device would completely erase during every forward bias period, but the photoconductive effects of the amorphous silicon photosensor presently limit this response. The large amplitude of this high frequency modulation obscured the rise and fall times of the optical response. Analog filtering was employed prior to the A/D sampling to more clearly determine the optical response of the modulator while suppressing the electrical response due to the driving frequency. Several low-pass filters were utilized. The cutoff frequency of these filters included 500, 200, and 100 Hz. Comparison of the resulting response curves using these varying filters revealed no characteristic change in the shape of the optical response while successfully suppressing most of the high frequency modulation. Figure 10(b) shows the optical response of the ferroelectric liquid crystal modulator using a low-pass analog filter with a 100 Hz cutoff frequency. The rise time, measured from the baseline to the maximum value, was 6 milliseconds. The fall time, from maximum value to the baseline, was 8 milliseconds. The cycle time is 14 milliseconds which corresponds to approximately 70 Hz. This response was taken near the optimum visibility of the modulator with 0.5 mW/cm^2 incident on the write side of the device. Furthermore, the device was driven with a 1 KHz, 10 V square wave with a +5 V DC offset.

The above response time measurements are summarized in Table 2.

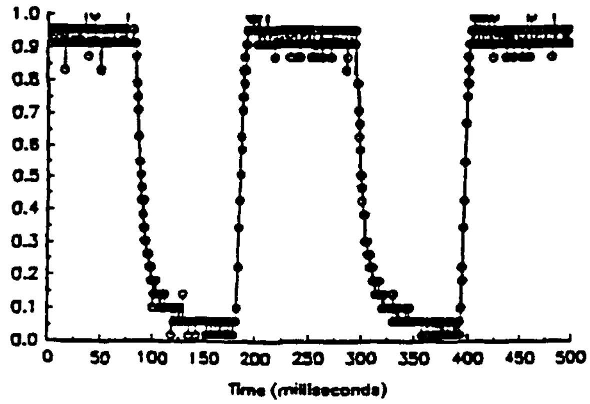
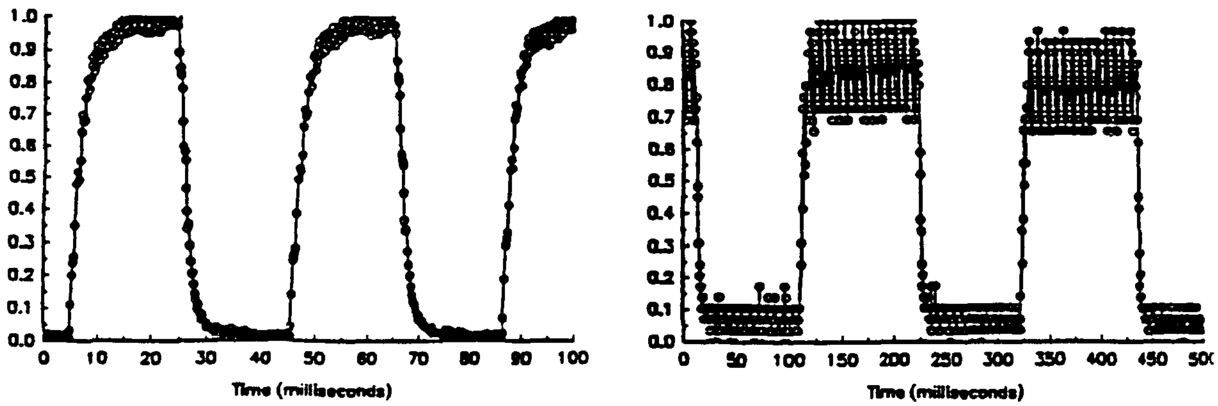


Figure 9. Response Data of a GEC-Marconi Research Spatial Light Modulator



(a) **(b)**

Figure 10. Response Data of the Ferroelectric Liquid Crystal SLMs

Table 2. Summary of Response Time Data for the Candidate SLMs

SLM	RISE TIME 10%-90% / 0%-100%	FALL TIME 10%-90% / 0%-100%	WRITE INTENSITY
HUGHES LCLV	22 msec / 35 msec	52 msec / 77 msec	100 μW/sq. cm.
PCU SLM (Hughes LCLV)	27 msec / 54 msec	77 msec / 140 msec	200 μW/sq. cm.
GEC-Marconi Research SLM	6 msec / 11 msec	19 msec / 40 msec	100 μW/sq. cm.
FLC #1 SLM	5 msec / 10 msec	4 msec / 8 msec	600 μW/sq. cm.
FLC #2 SLM	------- / 6 msec	------ / 8 msec	500 μW/sq. cm.

V. CONCLUSION

Key performance parameters of several optically-addressed spatial light modulators have been experimentally determined. These parametric measurements include maximum resolution, visibility, and response time of Hughes LCLV, GEC-Marconi Research SLM, and ferroelectric liquid crystal SLMs. The above measurements are not necessarily intended to present absolute values for the performance of the candidate modulators; however, they do provide an accurate means of comparing SLMs because identical test techniques were used.

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